

# THE DARK SIDE OF THE UNIVERSE \*

JOSEPH SILK

*Department of Astrophysics, Keble Road,  
Oxford OX1 3RH, England  
E-mail: silk@astro.ox.uk*

Most of the matter in the universe is invisible. I review the status of dark matter and describe how both the theory of galaxy formation and novel types of experimental searches are revitalizing attempts to find non-baryonic dark matter.

## 1 Introduction

This is an interesting time for dark matter studies. Direct and indirect searches will soon be capable of exploring most of the allowable parameter space for the elusive stable SUSY relics that are the favoured CDM candidate. Gravitational lensing is mapping the distribution of dark matter in halos and over larger scales with unprecedented precision.

The nature of the dark matter still almost completely eludes us. Nevertheless, there are many conjectures and proposed searches for dark matter signatures. In this review, I present an historical summary of the dark matter problem, review our present understanding of the distribution of dark matter and the various candidates for baryonic and non-baryonic dark matter, and describe the implications of particle dark matter for galaxy formation.

## 2 A brief history of dark matter probes

### 2.1 Galaxy clusters

The quantitative case for dark matter was first made by Zwicky<sup>1</sup> in 1933 for the Coma cluster of galaxies. He used galaxy peculiar velocities to estimate the virial mass, which he compared with the stellar mass, estimated from the luminosity. This method is essentially unchanged today, and modern applications of the virial theorem yield a similar value of mass to luminosity, of about  $300 M_{\odot}/L_{\odot}$ . However the uncertainties are large. Optical measurements utilizing the x-ray luminosity yield the emission measure and temperature from which one may derive the pressure gradient, and at submillimeter wavelengths,

---

\*TO APPEAR IN *2001: A SPACETIME ODYSSEY* (WORLD SCIENTIFIC, SINGAPORE)

the Sunyaev-Zeldovich effect directly yields the electron density. These give similar values of  $M/L$ , but again, the uncertainties are at least 50 percent.

Gravitational lensing has provided a direct measure of dark mass, determining the total surface density within the Einstein radius. These measurements make no assumptions about virialization of the gas, any deviations from isothermality, sources of nonthermal gas or velocity anisotropy. There are already hints from some large-scale shear studies that the inferred mass-to-light ratios, may differ from those inferred from large redshift surveys. For example, it is claimed that (Wilson, Kaiser and Luppino 2001)<sup>2</sup> the early-type galaxies trace the mass density at  $z \sim 0.5$ , resulting in  $\Omega_m \approx 0.1$  if any contribution from late-type galaxies is neglected. Weak lensing studies of groups (Hoekstra et al. 2001)<sup>3</sup> also lead to a relatively low  $(M/L)_B = 183 \pm 80h$  at  $z = 0$ , about half the value typically found for rich clusters (e.g. Carlberg et al. 1997).<sup>4</sup> Independent techniques for inferring cluster masses exist, but usually involve additional assumptions. For example, deduction of masses from studies of x-ray emission from the diffuse intracluster gas usually requires such assumptions as hydrostatic equilibrium of the gas and neglect of non-thermal support. This result is quantified in a study of x-ray clusters, which finds that  $(M/L)_v \approx 170(T/1\text{keV})^{0.3}$  (Bahcall and Comerford 2001).<sup>5</sup>

There is an interesting corollary of this result. If  $\Omega_m \approx 0.3$ , as many large-scale studies, e.g. of redshift-space distortions, suggest, then  $(M/L)_v \approx 300$  for typical regions of the universe that are unbiased, adopting  $(M/L)_v \approx 1400\Omega_m h$  as the canonical normalisation. This supports the usual assumption that the scale of galaxy clusters probes such representative regions, despite the fact that clusters predominantly contain early-type galaxies.

The reason for the differences between the different environments might be due to a systematic decrease of  $M/L$  in less dense clusters, in the outer regions of rich clusters and in the field, relative to the cluster value. The differences are indeed likely to be associated with galaxy type: the cores of rich clusters are dominated by spheroid-dominated (early-type) galaxies, but the outer parts of clusters and the field are dominated by disk-dominated (late-type) galaxies. Nevertheless, the trend in cluster mass-to-light ratios is most simply understood if the efficiency of galaxy formation at incorporating baryons into stars in galaxies in low density environments is about twice that for galaxies in massive clusters.

There may be an increase of cluster  $M/L$  with increasing cluster central density because denser clusters are older and would have undergone more passive evolution. However any significant evolution, e.g. as much as a magnitude, might be hard to reconcile with the similar fundamental plane relation (and hence  $M/L$  range) found for early-type field and cluster galaxies (van

Dokkum et al. 2001).<sup>6</sup>

Since approximately two-thirds of the optical ( $B$ -band) light density of the universe is produced by disk-dominated (late-type) galaxies, it follows, taking these  $M/L$  estimates at face value, that these galaxies are associated, presumably via their dark halos, with about a third of the mass in the universe. It is therefore not surprising that early-type galaxies trace the mass.

## 2.2 Galaxy halos

In the 1960's, the dark matter content of spiral galaxies was extensively explored by Rubin at optical wavelengths, using  $H\alpha$  radial velocity measurements of HII regions and by Roberts at 21cm, using the diffuse atomic interstellar medium as a dynamical probe of radial velocities. Modern observers have used rotation curves to explore the decomposition of the inner parts of galaxies into disk, bulge and dark halo contributions. Within the optical region (e.g. the half-light radius or typically several kpc), up to half of the matter contributing to the rotation curve may be non-baryonic (but see discussion below). Disks extend to 50 kpc or more for typical spirals and non-baryonic matter accounts for  $\sim 90$  percent of the dynamical mass. The inferred total  $M/L$  ratio is typically in the range 10 to 50. A self-similar profile with only two free parameters, central density and concentration, fits most dark halos.

Low surface brightness spirals provide an exception to the universal profile fit. These systems are everywhere dark-matter dominated and display a variety of central cores which are often soft and rarely cuspy (van den Bosch and Swaters 2001).<sup>7</sup>

## 2.3 Galaxy redshift surveys

On very large scales, from 10 to 100 Mpc, progress has awaited the results from the large redshift surveys. The pioneering CfA surveys of the 1980s and 1990s with some 8000 redshifts culminated in the Las Campanas survey of 25000 galaxies in the mid 1990s. The situation changed little until the AAT 2DF ushered in the first 250,000 galaxy survey in 2001, followed closely by SDSS with the prospect of  $10^6$  redshifts by 2003. The universe is well-sampled to  $z \sim 0.3$ .

An important result is that redshift space distortions allow measurement of the dark matter content, subject to the unknown bias of mass relative to light. If the bias is assumed to be scale-independent and described by a

spectrum of density fluctuations with variance

$$\sigma^2 = \langle (\delta\rho/\rho)^2 \rangle / \langle (\delta\rho/\rho)^2 \rangle_{galaxies},$$

normalized to a fiducial scale of  $8h^{-1}\text{Mpc}$  where  $\langle (\delta\rho/\rho)^2 \rangle_{galaxies} \approx 1$ , one infers via deviations from the Hubble flow as measured by redshift-space distortions that (Peacock et al. 2001)<sup>8</sup>  $\Omega^{0.6}\sigma_8 = 0.43 \pm 0.07$ . An independent approach uses the shape of the power spectrum, combining the 2DF galaxy redshift survey with cosmic microwave background fluctuations, to obtain a virtually identical result (Efstathiou et al. 2001).<sup>9</sup> The inferred global  $M/L$  is  $300\sigma_8^{-1.7}$ . Theory suggests that on scales above 10 Mpc which are sampled by the large-scale surveys, one would anticipate little or no bias ( $\sigma_8 \approx 1$ ). Hence  $\Omega_m \approx 0.3$ .

#### 2.4 The baryon fraction

Independent measures of  $\Omega_m$  confirm that  $\Omega_m \approx 0.3$ , for example both via the evolution of the cluster number density (Bahcall and Fan)<sup>10</sup> and the observed cluster baryon fraction (Arnaud and Evrard 1999)<sup>11</sup>. The universal primordial baryon fraction is well measured from light element nucleosynthesis to be 0.05 (adopting a Hubble content of 65 km/s/Mpc). The baryon fraction of 15% which is actually measured in rich galaxy clusters requires the universal dark matter density to be  $\Omega_m \approx 0.3$ , and confirms the result inferred from large-scale structure studies.

However a baryon fraction of 15% can only be reconciled with galaxy halo and disk masses, and galaxy formation, if while beginning with  $\Omega_b/\Omega_m \approx 0.15$ , one ends up with  $\Omega_*/\Omega_m \approx 0.07$ , where  $\Omega_*$  is the observed luminous baryon density at  $z = 0$ . This constraint comes from several independent arguments, and one requires about 50 percent of the baryons to either be ejected or to hitherto be undetected.

The Milky Way mass budget suggests that the galactic disk and spheroid amount to  $7 \times 10^{10} M_\odot$  in a halo of about  $10^{12} M_\odot$ . A more quantitative confirmation of this argument comes from examining the adiabatic compression of the dark halos by cooling baryons, both analytically in comparison with the velocity function (Kochanek and White 2001; Kochanek 2001)<sup>12,13</sup> and via numerical simulation modelling of the Milky Way in comparison with the rotation curve (Klypin, Somerville and Zhao 2001).<sup>14</sup> The inference that more baryons cooled than are seen in stars is a manifestation of the so-called cooling catastrophe. There appears to be a similar shortfall in the local mass in old stars as seen in  $K$ -light compared to the rest-frame ultraviolet luminosity density observed in star-forming galaxies at  $z \sim 3$ , for reasonable extinction

corrections (Cole et al. 2001).<sup>18</sup>

The obvious solution to this problem involves either expelling half the the gas or hiding the gas before it forms stars. Both hypotheses are controversial since supernovae seem incapable of driving so much gas out of the early galaxy (MacLow and Ferrara 1999)<sup>19</sup> and there is little evidence for a substantial halo component of dark baryons either in diffuse gas, which would have been detected, or in compact form, as in MACHOs, over the mass range  $10^{-7} \lesssim M_{MACHO} \lesssim 10M_{\odot}$  (Milsztajn and Lasserre 2000).<sup>16</sup>

### 3 What is the dark matter?

There are two distinct varieties of dark matter. There is both baryonic dark matter and non-baryonic matter. Each provides distinct difficulties.

#### 3.1 Baryonic dark matter

Primordial nucleosynthesis has convincingly predicted the baryon fraction of the universe to be  $\Omega_b \approx 0.05$ . There is an independent estimate of  $\Omega_b$  from the fluctuations in the cosmic microwave background, and in particular from the height of the second acoustic peak. One needs to assume a cosmological model, such as that of a flat universe, and the predominance of the adiabatic mode of primordial fluctuations for this measurement to be entirely free of degeneracy. However flatness is unambiguously measured from the location of the first peak, and inflationary cosmology guarantees the emergence of adiabatic fluctuations from quantum fluctuations in the presence of a single scalar inflaton field.

Direct observations of the baryon fraction that utilize the luminous components of galaxies and the absorption of the diffuse intergalactic medium give values of  $\Omega_b$  that at  $z \approx 3$  agree with the primordial nucleosynthesis value (most notably via Lyman alpha forest absorption) but at  $z \approx 0$  fall short by a factor of around 4. The only reasonable conclusion is that there are dark baryons: 75 percent of the baryonic component has somehow avoided the process of luminous galaxy formation or of being incorporated into the cold/warm component of the intergalactic gas that is associated with the Lyman alpha absorbing clouds detected at low  $z$ .

A diffuse, warm intergalactic medium component at  $10^5$  to  $10^6$ K may account for some of the baryonic dark matter. However, the numerical simulations which predict its existence and heating via gravitational accretion shocks around galaxies and galaxy clusters make a plausible case for at most only 30-40 % of the baryonic dark matter to be in this form.

One might expect that local processes of star formation selected the baryons seen in stars, leaving the remaining baryons in the vicinity of the stellar components. This is not necessarily the case, however, as the Lyman alpha forest tracers of high redshift baryons are only weakly correlated, or even anti-correlated, with respect to luminous galaxies. Indeed, the nearby ( $z \lesssim 0.1$ ) Lyman alpha absorbing clouds account for some 20-25% of the baryons in low column density warm, photo-ionized gas (Shull 2001).<sup>17</sup> With say 10% in stars, at least 25% of the baryons are unaccounted for.

Presumably these “missing” dark baryons are today in galaxy halos. In the absence of any further indications of cold intergalactic baryons, searches have therefore focussed on dark halo baryons. Halo searches have failed to come up with dominant amounts of baryonic dark matter. The best motivated candidate, MACHOs, amount to no more than 20 percent of the halo mass between the solar circle and the LMC (Alcock et al. 2000).<sup>15</sup> However this is almost enough to account for the remaining cooled baryons: if the MACHO limit is saturated, there is about twice as much mass in MACHOs as in stars.

Of course MACHOs remain the only claimed detection although their halo distribution is controversial. If indeed the MACHOs are a halo component, then old white dwarfs provide a possible MACHO candidate. While the MACHO experiment does permit a significant halo mass fraction in the form of stellar remnants, overproduction of chemical elements strongly argues against the interpretation of all of the MACHOs as being white dwarfs (Fields, Freese and Graff 2001).<sup>20</sup> The claimed detection of halo white dwarfs at the few percent level (Oppenheimer et al. 2000)<sup>21</sup> has been strongly criticized on kinematic grounds, but chemical abundance anomalies in old halo stars and in extragalactic deuterium are consistent with the proposed abundance of halo white dwarfs and with the existence of the inferred primordial population of intermediate mass stars (Fields et al. 2001).<sup>22</sup>

Alternative halo baryonic dark matter candidates are elusive. Cold  $H_2$  clumps are an intriguing possibility since such gas would have evaded detection in a halo component. There may be a large  $H_2$  reservoir: indeed it has been argued that the HI in the interstellar medium is photodissociated  $H_2$  (Allen 2001).<sup>23</sup> However the observational hints of extensive  $H_2$  that support this hypothesis suggest that the total mass detected in this form in the inner galaxy is unlikely to exceed the cold HI mass. Another (admittedly theoretical) difficulty with this argument is that while there is some evidence for diffuse cold interstellar  $H_2$ , cold  $H_2$  clumps pose a stability problem: why don't they form stars?

### 3.2 Non-baryonic dark matter

Baryonic dark matter only accounts for between 10 and 25 percent of the dark matter. The nature of the non-baryonic dark matter is unknown. However SUSY has provided motivated candidates among the class of the lightest stable particles, generically called neutralinos. This stems from the remarkable coincidence that with  $\Omega_m \approx 0.3$ , as required by large-scale structure observations, the particle annihilation cross-section is required via thermal freeze-out at  $T \approx m_x/20$  to satisfy  $\langle\sigma v\rangle_{ann} \approx 3 \times 10^{-26} (0.1/\Omega_m h^2) \text{cm}^3 \text{s}^{-1}$ , within the range expected for typical WIMP candidates. The prime uncertainty in translating this constraint into WIMP search parameter space is that even minimal SUSY models allow a range of several orders of magnitude in the cross-section predicted for a specified WIMP mass  $m_x$ . Accelerator constraints impose the lower bound  $m_x \gtrsim 50 - 100 \text{GeV}$  (Baltz and Edsjo 2001; Ellis, Nanopoulos and Olive 2001).<sup>24,25</sup> Hence annihilation signatures are potentially detectable by high energy astrophysics experiments that search for diffuse halo gamma rays, neutrinos or even cosmic ray fluxes generated in the halo.

High resolution simulations provide a new approach to studying weakly interacting dark matter. Halos are found to be clumpy, the substructure persisting through successive mergers and not necessarily being fully resolved by the best simulations to date. One consequence of the substructure is a large population of satellite galaxies, approximately increasing in abundance as  $dN/dM \propto M^{-2}$ . In fact the low observed frequency of dwarf satellites argues against a halo that is as highly clumped as suggested by the CDM simulations. Independent confirmation of this local result comes from high redshift observations of the gas-rich pregalactic phase provided by the data on damped Lyman alpha clouds seen towards quasars. A recent survey (Prochaska and Wolfe 2001)<sup>26</sup> fails to find the predicted excess of low line width clouds relative to clouds with large ( $\sim 200 \text{km s}^{-1}$ ) velocity dispersions.

Quenching of star formation by early ( $z \sim 10$ ) photoionization may help make the dwarfs invisible (Gnedin 2000; Somerville 2001)<sup>27,28</sup>. Overheating of the disk could still pose a problem, although accounting for the observed thinness of the galactic disk may be less of a difficulty than previously suggested if  $\Omega_m$  is low (Font and Navarro 2001)<sup>29</sup>.

The simulations also predict excessive concentration of the dark matter, cuspieness of the halos, and loss of angular momentum via dynamical friction, all of which seem to result in signatures that appear to contradict the observational evidence from studies of the stellar component.

Several indirect observational probes suggest that in addition to the substructure issue, the dark matter concentration and cuspieness are rather less

extreme than predicted by the simulations. The high resolution simulations generally find a dark matter profile with a central cusp  $\rho \propto r^{-1.5}$  for galaxy mass halos (Moore et al. 1999; Jing and Suto 2000; Klypin et al. 2001).<sup>30,31,32</sup> However observations of dwarf LSB spirals find little, if any, evidence for central cusps.

The predicted concentration for the typical dark halo in a  $\Lambda$ CDM model results in about a 50% dark matter contribution within 2 disk scale lengths. With regard to Milky-Way type galaxies, the evidence suggests that dark matter cusps do not exist in the presence of bars, both from dynamical arguments centering on dynamical friction of the rapidly rotating bars on the dark matter that require the baryons in bars to be self-gravitating (e.g., Debattista and Sellwood 2000)<sup>33</sup> and the associated disk to be maximal, and from the microlensing and stellar population modelling of the inner Milky Way in combination with the observed rotation curve (Binney and Evans 2001).<sup>34</sup> This latter constraint limits the axially symmetric non-baryonic dark matter contribution within the solar circle to be less than or of order 10 percent. Of course the Milky Way has a bar: however one well-studied nearby spiral with no evident bar appears to require a  $\sim 50\%$  dark matter contribution within the optical disk for a submaximal disk model (Kranz, Slyz and Rix 2001) to account for features in the measured rotation curve.<sup>35</sup>

Tilting the primordial spectrum to the red lowers the small-scale power, and lowering of  $\Omega_m$  reduces the concentration of halo dark matter. However these patchwork solutions do not completely alleviate the substructure and concentration problems, and a red tilt is likely to create other difficulties.

We do not know if the resolution of these issues lies in the domain of fundamental gravity, particle physics via tinkering with the nature of the dark matter particles or astrophysics via modification of the dark halo properties. Fundamental changes in the gravity law may allow one to modify Newton's laws, either by a phenomenological approach that fits rotation curves with one additional parameter and no dark matter, but is not Lorentz invariant (Milgrom 1999)<sup>36</sup>, or by invoking higher-dimensional gravity to introduce gravitational interactions with adjacent branes (e.g., Arkani-Hamed et al. 2000)<sup>37</sup>

Adjusting the neutralino properties, e.g. by allowing the particles to be self-interacting or fluid-like, modifies the halo properties, although not necessarily in a completely satisfactory direction (Yoshida et al. 2000a; Yoshida et al. 2000b; Meneghetti et al. 2001).<sup>38,39,40</sup> Warm dark matter does not solve the cusp problem (Avila-Reese et al. 2001; Knebe et al. 2001)<sup>41,42</sup>, although the substructure problem is largely resolved (Bode, Turok and Ostriker 2001).<sup>43</sup> The median satellite distances from the Milky Way, already in disagreement with  $\Lambda$ CDM model predictions, are considerably aggravated by warm dark



matter (Klypin 2001, private communication). More complex modifications of particle matter have been invoked.

Alternatively, early dynamical processes involving non-axially symmetric distributions of baryons could couple the baryons to the dark matter, erode some of the cusiness and substructure, and reduce the concentration. This may happen dynamically via black hole mergers or via a combination of the deceleration of a rapidly rotating bar and black-hole driven outflows (Binney, Gerhard and Silk 2001).<sup>44</sup> This latter approach is more difficult to simulate and quantify, but some dynamical modification of the dark matter distribution clearly must occur in the presence of bar formation and dissolution, supermassive black hole formation, and massive outflows.

One can imagine the following sequence of events. A merger between protogalaxies results in formation of a massive, rapidly rotating, transient bar. The non-axially symmetric matter distribution exerts strong tidal torques on the gas that is driven into the centre of the galaxy to form a supermassive black hole. Meanwhile the dynamical friction exerted by the bar heats and spins up the halo core within a region containing roughly equal amounts of baryons and dark matter. The bar contracts before it dissolves as the black hole grows, and the halo core expands. The inner galaxy is now baryon-dominated. Outflows driven by accretion of gas onto the supermassive black hole sweep out substantial amounts of baryons, of order 50%, until the core contains roughly equal amounts of dark matter and baryons, when baryon-driven growth of the black hole becomes less important. The outflows consist of low angular momentum baryonic matter. The disk forms by late infall of high angular momentum baryons.

This suggests that all spheroids underwent an early quasar-like phase. The following problems *may* be solved: the dark matter cusp is erased, the concentration is reduced, dwarfs are stripped of gaseous baryons, baryons are ejected in a substantial amount, and disk sizes are enhanced because disks form from high angular momentum gas. While these claims are meant only to be taken qualitatively, the point is clear: astrophysical processes may strongly modify the dark halo properties.

#### 4 “Observing” non-baryonic dark matter

Dark matter particles are majorana-like, and their annihilations provide a potentially powerful signature. There have been tentative reports of high energy  $e^+$  and diffuse high galactic latitude gamma ray detections. However the fluxes measured are up to 100 times in excess of what would be predicted for a uniform CDM halo (Baltz and Edsjo 1999; Baltz et al. 2001)).<sup>45,46</sup> In

fact, halos are plausibly clumpy, as revealed by high resolution simulations of halo formation, but it is not known whether the clumpiness persists until the present epoch and suffices to account for the enhanced fluxes.

Ideally, one would like a direct probe of the dark matter. This may be provided within our galaxy or in nearby galaxies by searching for the annihilation signal which will be enhanced by the concentration of CDM towards the inner halo, and in particular by the possibility of a central cusp. Again, such cusps are predicted by the simulations to have  $\rho \propto r^{-1.5}$ . In fact, not only are such cusps not seen, but they would not significantly enhance the annihilation signal.

However the situation changes dramatically in the presence of a central supermassive black hole (SMBH). Such objects are virtually ubiquitous in spheroids, and their mass correlates tightly with spheroid velocity dispersion over the entire SMBH mass range, with the median black hole mass fraction equal to 0.13% that of the bulge (Ferrarese and Merritt 2001; Gebhardt et al. 2001).<sup>47,48</sup> The supermassive black holes range in mass from the SMBH in the Milky Way bulge ( $\sim 2.6 \times 10^6 M_\odot$ ) to NGC 4258 ( $\sim 4 \times 10^7 M_\odot$ ), these being the two unchallengeable supermassive black hole cases, up to M87 ( $\sim 3 \times 10^9 M_\odot$ ).

There are two effects. Firstly, the halo forms via mergers of subsystems containing smaller SMBHs. This is expected in hierarchical halo formation. As the smaller SMBH spirals into the dominant halo, the inner halo cusp is smoothed, to a profile that, for minor mergers, approaches  $\rho \propto r^{-0.5}$  (Nakano and Makino 1999; Merritt and Cruz 2001)<sup>49,50</sup>. For major (equal mass) mergers, a steeper profile results,  $\rho \propto r^{-1}$  (Milosavljevic and Merritt 2001).<sup>51</sup>

Stellar cusps have been studied in ellipticals. Power-law cusps are found in faint spheroids and in rotating systems, while luminous ellipticals often have central soft cores that are inferred to have been generated dynamically by the orbital decay of the central SMBH (Faber et al. 1997).<sup>52</sup> A range of dynamical histories is inferred that must depend on whether the SMBH grew as a result of a dynamical merger or by gas accretion.

CDM continues to accrete while the central SMBH grows by accreting more mass via baryonic dissipation in the early quasar outburst, associated with, and driven by, gas infall onto the SMBH, that occurs during the gas-rich protogalactic phase. The dominant process underpinning the bulk of the SMBH growth must be baryonic dissipation, as dynamical growth by black hole or stellar mergers is simply too slow to produce a significant space density of ultraluminous quasars at  $z \lesssim 6$ , as observed. This is especially true for disk galaxies where significant black hole growth by black hole mergers following mergers of galaxies containing black holes would probably have been overly disruptive of the fragile disks.

The Milky Way galaxy, with a relatively insignificant spheroid, is a candidate for SMBH growth by accretion and a dense dark halo cusp. Any mergers in the Milky Way must have occurred long ago, to avoid disk disruption, and the SMBH is likely to have acquired its present mass of  $2.6 \times 10^6 M_\odot$  as a result of gas accretion. There is even now a large reservoir of gas in the galactic centre, both in molecular gas and in the inferred ejecta from OB stars, although the current accretion rate of the SMBH is extraordinarily low at the present epoch. The result is that, almost certainly in our own galaxy, the CDM density around the SMBH is locally enhanced by the adiabatic response of the CDM to the SMBH growth.

Whatever the original dark matter core, the central cusp becomes denser and steeper as a consequence of quasi-adiabatic SMBH growth. The inner cusp develops within the zone of gravitational influence of the SMBH,  $GM_b/\sigma^2$ , of order a parsec for the Milky Way. This inner cusp,  $\rho \propto r^{\gamma'}$ , is always steeper than  $\rho \propto r^{-1.5}$ , for *any* underlying halo profile  $\rho \propto r^\gamma$  :  $\gamma' = \frac{9-2\gamma}{4-\gamma}$ , and yields observable potentially fluxes of high energy neutrinos (Gondolo and Silk 1999).<sup>53</sup>

The resulting signal would be divergent, except that sufficiently close to the SMBH (within  $< 100$  Schwarzschild radii), the annihilation time becomes so short that the CDM density declines abruptly. Thus a central supermassive black hole further enhances the annihilation signal by concentrating dark matter during the halo formation phase. The predicted signals (Bertone, Sigl and Silk 2001, and in preparation)<sup>54</sup> include coincident point-like radio and gamma ray emission which are consistent with observations of SagA\* with regard to both flux and spectral signatures. Future observations of terrestrial muon fluxes induced by high energy neutrinos propagating through the earth, for example with deep underwater detectors such as ANTARES, should help test this conjecture.

## Acknowledgments

I thank Gianfranco Bertone, Anatoly Klypin and Guenter Sigl for fruitful discussions and ongoing collaborations.

## References

1. F. Zwicky, *Helv. Phys. Acta.* 6 (1933) 510.
2. G. Wilson, N. Kaiser and G. Luppino, *Astrophys. J.* 556 (2001) 601.
3. H. Hoekstra et al. , *Astrophys. J.* 548 (2001) L5.
4. R. Carlberg et al., *Astrophys. J.* 478 (1997) 162. 601.

5. N. Bahcall and J. Comerford, (2001) astro-ph/0109366.
6. P. van Dokkum et al., , Astrophys. J. 553 (2001) L39.
7. F. van den Bosch and R. Swaters, MNRAS 325 (2001) 1017.
8. J. Peacock et al., Nature 410 (2001) 169.
9. G. Efstathiou et al. M., astro-ph/0109152 (2001), MNRAS, submitted.
10. N. Bahcall and X. Fan, Astrophys. J. 504 (1998) 1.
11. M. Arnaud and A. Evrard, MNRAS, 305 (1999) 631.
12. C. Kochanek and M. White, Astrophys. J. (2001), in press.
13. C. Kochanek, in *The Dark Universe*, ed. M. Livio (2001), CUP, in press.
14. A. Klypin, R. Somerville and H. Zhao (2001), in preparation.
15. M. MacLow and A. Ferrara, Astrophys. J. 513 (1999) 142.
16. A. Milsztajn and T. Lasserre, XIXth International Conference on Neutrino Physics and Astrophysics, Sudbury (2000), astro-ph/0011375.
17. J. Shull, astro-ph/0107473 (2001), in *Extragalactic Gas at Low Redshift*, ASP Conference Series, in press.
18. S. Cole et al., MNRAS, 326 (2001) 255.
19. C. Alcock et al., Astrophys. J. 542 (2000) 81.
20. B. Fields, K. Freese, and D. Graff, Astrophys. J. 534 (2001) 265.
21. B. Oppenheimer et al., Science 292 (2001) 698.
22. B. Fields et al. Astrophys. J. (2001), in press.
23. R. Allen, astro-ph/0103025 (2001), in *Gas and Galaxy Evolution*, eds. J. Hibbard et al., in press.
24. E. Baltz and P. Gondolo, astro-ph/0105249 (2001) Phys. Rev. Lett, in press. 65.
25. J. Ellis, D. Nanopoulos and K. Olive, Phys. Lett., 508 (2001) 65.
26. J. Prochaska and A. Wolfe, astro-ph/0108154 (2001), Astrophys. J., submitted,
27. N. Gnedin, Astrophys.J. 542 (2000) 535.
28. R. Somerville, astro-ph/0107507 (2001), Astrophys. J. , submitted,
29. A. Font and J. Navarro, Astrophys. J. (2001), submitted, astro-ph/0106268.
30. B. Moore et al., Phys. Rev. D. (2001), in press, astro-ph/0106271.
31. Y. Jing and Y. Suto, astro-ph/0001288 (2000), 4th RESCUE Symposium on Birth and Evolution of the Universe, in press.
32. A. Klypin et al., Astrophys. J. 554 (2001) 903
33. V. Debattista and J. Sellwood, Astrophys. J. 543 (2000) 704.
34. J. Binney and N. Evans, astro-ph/0108505 (2001), MNRAS, submitted.
35. T. Kranz, A. Slyz and H.-W. Rix, Astrophys. J. (2001) in press.
36. M. Milgrom, in Dark Matter in Astroparticle and Particle Physics, IOP, eds. H. Klapdor-Kleingrothaus and L. Baudis, (1999) p. 443.

37. N. Arkani-Hamed et al., JHEP, 12 (2000) 10.
38. N. Yoshida et al., Astrophys. J. 544L (2000a) 87.
39. N. Yoshida et al., Astrophys. J. 535L (2000b) 103.
40. M. Meneghetti et al., MNRAS, 325 (2001) 435.
41. V. Avila-Reese et al., Astrophys. J. (2001) in press.
42. A. Knebe et al., MNRAS (2001), in press.
43. P. Bode, N. Turok and J. Ostriker, Astrophys. J. 556 (2001) 93.
44. J. Binney, O. Gerhard and J. Silk, MNRAS, 321 (2001) 471.
45. E. Baltz and J. Edsjo, PRD, 59 (1999) 023511.
46. E. Baltz et al., astro-ph/0109318 (2001).
47. L. Ferrarese and D. Merritt, Astrophys. J. 539 (2001) 9.
48. K. Gebhardt et al. Astrophys. J. 539 (2001) 13.
49. T. Nakano and J. Makino, Astrophys. J. 510 (1999) 155.
50. D. Merritt and F. Cruz, Astrophys. J. 551 (2001) L41.
51. M. Milosavljevic and D. Merritt, Astrophys. J. (2001) in press.
52. S. Faber et al., Astron. J., 114 (1997) 1771.
53. P. Gondolo and J. Silk, PRL, 83 (1999) 1719.
54. G. Bertone, G. Sigl and J. Silk, MNRAS, 326 (2001) 799.